CORRELATION AND PREDICTION OF PROPAGATION TIME-DELAYS ALONG EARTH-SPACE LINKS (U)

HAIM SOICHER, Ph.D.
COMMUNICATIONS SYSTEMS CENTER
US ARMY COMMUNICATIONS RESEARCH & DEVELOPMENT COMMAND
FORT MONMOUTH, NJ 07703

JUN 1980

INTRODUCTION

High precision in radar detection, in earth-satellite orbit determination, and in satellite navigation necessitates that the signal data used be corrected for the errors imposed by the ionosphere.(1) Signal time-delays, or equivalently range errors, are always encountered in transionospheric measurements because the electromagnetic propagation velocity in the medium is slightly less than the free-space velocity. For frequencies at VHF and above, an excess time delay is inversely proportional to the square of the frequency and is directly proportional to the integrated electron density along the propagation path (i.e., total electron content (TEC) measured in units of el/m^2). Thus, if TEC is known, or is measured in real time, a perfect correction to ranging can be performed. The TEC may be measured in real time, provided the user has dual-frequency capabilities. Since the ionosphere is a dispersive medium, the relative time delays (or phase differences) between the two frequencies may be used to eliminate the error introduced by the TEC. However, substantial simplification in user equipment could be realized if only one frequency were utilized. Time delays would then be determined by forecasting techniques based on media models. Because of the spatial and temporal variability of the ionospheric electron density, the time-delay errors vary with geographic location, target (or source) altitude, and time. For improved accuracy, the forecasting techniques should be supported by periodic updating of data (preferably in real-time) at specified locations. The question arises as to the extent of the geographic area, surrounding a station having real-time TEC-determination capabilities, within which TEC values could be interpolated with acceptable accuracy. In other words, could TEC be determined at location A if a real-time measurement were taken at a different location B, and what would be the geographic constraints on A and B.

To this end, a specific investigation designed to determine the correlation (based on linear regression analysis) between TEC values at Fort Monmouth, NJ (40.18°N, 74.06°W) and at Richmond, FL (25.60°N 80.40°W), and between TEC values at Richmond, FL, and Anchorage, AK (61.04°N, 149.75°W) was undertaken. Beacon transmissions from geostationary satellites were used to determine the TEC at the stations by means of the Faraday rotation technique.

The subionospheric points for the Richmond-Fort Monmouth stations (i.e., the geographic locations where the ray paths to the ATS-6 Satellite [2,3] (located at 94°W) intersect a "mean" altitude of 420 km) were 36.5°N, 76.6°W and 23.6°N, 81.6°W, respectively. Thus, the "representative" TEC for the two stations was separated by ~13° in latitude and by ~5° in longitude (corresponding to a 20-minute difference in local time). The subionospheric points for the Richmond-Anchorage stations (monitoring the SMSI Satellite (located at 105°W), and the ATS-6 (located at 140°W),respectively) were 22.5°N, 82.7°W and 54.3°N, 147.3°W respectively. The "representative" TEC was separated by ~31.8° in latitude and ~63.8° in longitude (corresponding to a 4 hour 15 minute difference in local time).

THE DATA

The daily variations of vertical TEC measured by the Faraday technique for the representative month of February 1975 at Fort Monmouth and at Richmond are shown in Fig. 1. The equivalent ionospheric signal delay times normalized to a frequency of 1.6 GHz (in the satellite navigation frequency band) are also indicated in this figure. The normal diurnal variation of TEC is evident, as is its day-to-day variability.

Figure 2 indicates the variation of the maximum daily correlation of the Fort Monmouth-Richmond data pairs for September 1974 and January, February, March, April, and May 1975. These were arrived at by comparing the TEC daily data sets at Fort Monmouth and Richmond. At first, the correlation coefficient was calculated for identical UT times. Then, the Richmond data was shifted in time with respect to the Fort Monmouth data at 15-minute intervals in the forward (+) direction and in the backward (-) direction. Correlation coefficients are calculated for up to ten shifts in the forward and backward direction. The maximum correlation coefficient as well as the number of shifts for which the maximum correlation coefficient is attained

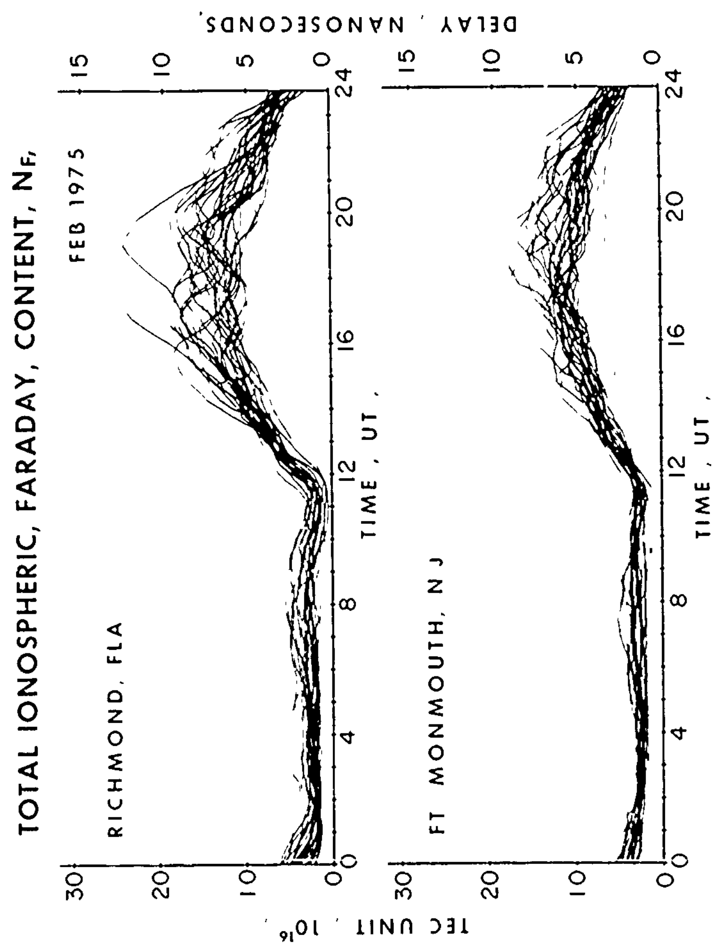

Figure 1: Total ionospheric (Faraday) electron content (N_F) at Fort Monmouth, NJ, and Richmond, FL, February 1975 (left ordinate: 1 TEC unit = 10^{16} el/m^2; right ordinate: time delay normalized to 1.6 GHz).

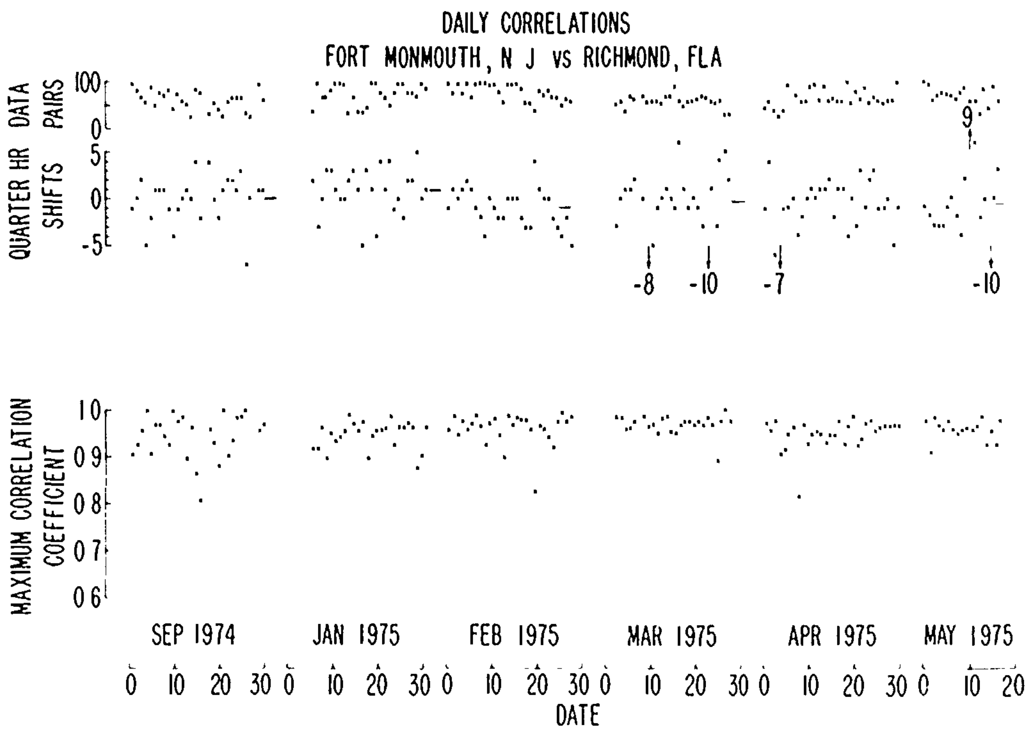

Figure 2: Variations of the maximum correlation coefficients of the Fort Monmouth, NJ, and Richmond, FL, daily data sets. Also indicated are the time shifts for which these were attained, their averages (–), and the number of data pairs used in analysis.

are indicated in the figure, as are the shifts' monthly averages. In addition, the number of data pairs available for the correlation analysis for each day (maximum of 96 data pairs, since the data is available at 15-minute intervals) is also shown in the figure.

In general, the correlation coefficients ranged between $\sim$ 0.9 and $\sim$ 1.0 with relatively few falling below 0.9. The lower values of the coefficients did not necessarily coincide with the sparsity of the available data. On the average, the coefficient was maximum for no shifts in September, for $\sim$1 shift in January, and for > (-1) shift for the other months. While most maximum coefficients occurred for $\pm$1 hour shifting ($\pm$ 4 fifteen-minute shifts), shifts of two hours and more were observed occasionally.

Figure 3 indicates the variation of the maximum daily correlation coefficients of the Richmond-Anchorage data pairs for October, November and December 1976, arrived at in a similar manner as above except that the data sets were moved to correspond in local time (i.e., zero shifts correspond to identical local time).

In general, the coefficients ranged from $\sim$ 0.8 and $\sim$1.0 with relatively few falling below 0.8. The bulk of the coefficients was above 0.9, which was the range of the Richmond-Fort Monmouth data. The correlation coefficient was, on the average, higher in October, declined in November, and declined further in December. This was undoubtedly due to the sunrise and sunset times at both locales. In mid-October the sunrise and sunset times (at 400 Km) at the sub-ionospheric points differed by about 15 minutes, while in mid-December they differed by about 45 minutes. Thus, in December the shape of the diurnal variation was considerably different for the two locales than in October. The result is a decrease in the magnitude of the correlation coefficients. On the average, the coefficients were maxima at $\sim$ -5 shifts in October, no shifts for November, and $\sim$ -2 shifts for December.

The next phase of the investigation was the effort to determine whether it is possible to accurately predict TEC at one locale from TEC at the other, using average regression lines obtained for the corresponding data sets. The technique employed was as follows: Average monthly regression lines were computed. In one case, average slopes as well as average intercepts of the regression lines at monthly intervals were computed. In a second case, average slopes were computed while the intercepts were forced to pass through a common data point for the two sets at a specific predawn time for each day. Having determined the average regression lines, TEC at one locale was calculated for a given TEC at the corresponding other

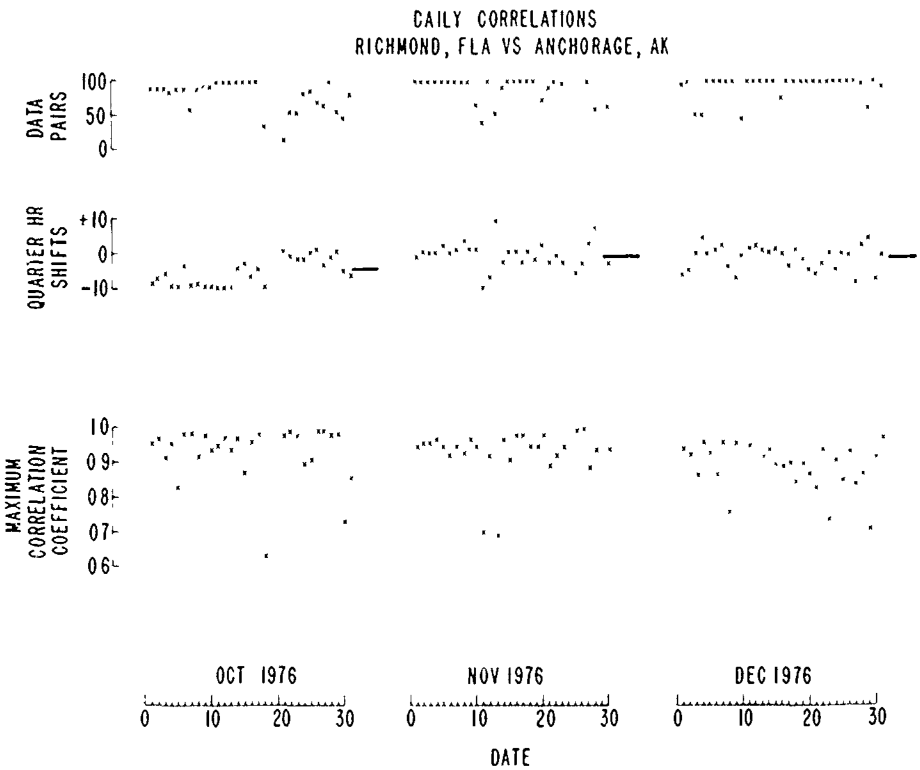

Figure 3: Variations of the maximum correlation coefficients of the Richmond, FL, and Anchorage, AK, daily data secs. Also indicated are the time shifts for which these were attained, their averages (-), and the number of data pairs used in analysis.

locale. The deviation (D_i) of the calculated TEC from its actual value at a particular time is then determined. This deviation, D_i, is then divided by σ_i, the monthly TEC standard deviation value at the same time. The average absolute value of this ratio, i.e., $|D|/\sigma$ was then computed for each day.

The results for the Fort Monmouth-Richmond data sets (i.e., predicting TEC at Richmond from TEC at Fort Monmouth) using average slopes and intercepts of the monthly regression lines are shown in Fig. 4. Also shown in the figure is the number of data pairs available for the analysis for each day (data is available at 15-minute intervals; ninety-six data points signify a full days data availability. Data is sometimes missing, due to turn-off of the satellite's beacons). The results using average slopes and intercepts of the monthly regression lines, but for the time period 1500-2100 UT, when the maximum diurnal TEC values occur are shown in Figure 5.

The results for the Richmond-Anchorage data sets (i.e., predicting TEC at Anchorage from TEC at Richmond for the same local time) using average slopes and intercepts of the monthly regression lines are shown in Fig. 6. The results using average slopes and intercepts of the monthly regression lines, but the time period 1500-2100 UT (for Richmond and the correspondingly shifted time for Anchorage), when the maximum diurnal TEC values occur are shown in Fig. 7.

DISCUSSION

As Fig. 4 indicates, the daily average of the ratios $\frac{|D|}{\sigma} = \frac{1}{N}\sum_{i=1}^{N}\frac{|D_i|}{\sigma_i}$ for Richmond is, for the most part, smaller than one, (i.e., on the average, the deviation of the computed Richmond TEC values from Fort Monmouth TEC values, is, in general, within the monthly standard deviation of the Richmond data). The diurnal behavior of the ratio is such that the ratio is higher during the night (when σ is small) than during the day. Some of the high values of this ratio are attributable to ionospheric effects during magnetically active periods, e.g., on September 15 and 18, 1974, large enhancement of TEC were observed in response to magnetic sudden commencements; on March 11, the K_p index ranged from 4^o to 7^-. The results of the figure also indicate that the ratio appears larger during the equinoctial period (September, March) than during the winter and spring months. This is observed despite the fact that the standard deviation during the equinoctial months was considerably higher than during the other months. Calculations using the average slopes of the regression lines and forcing the lines to pass through actual common points at 0200 UT indicate that the ratio, in general, does not

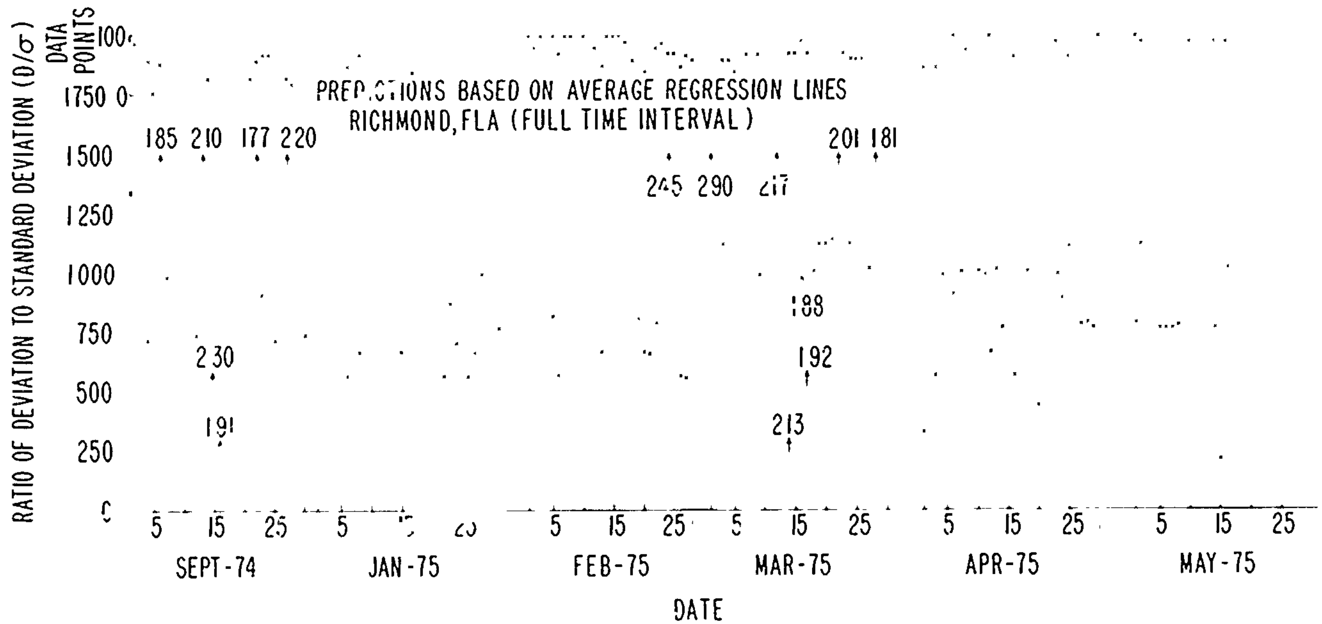

Figure 4: The variation of the ratio $|D| / \sigma$ for Richmond, FL, for the time period September 1974, and January 1975–May 1975 calculated for full diurnal periods by average regression lines obtained by Fort Monmouth, NJ–Richmond, FL, data sets. ($|D| \equiv$ diurnal average of the deviations of the computed TEC values from observed ones; $\sigma \equiv$ monthly standard deviation of the Richmond data). The arrows and the corresponding numerical values are for those values of the ratio which exceed the scale of the Figure. Also indicated in the upper portion of the Figure are the number of TEC data pairs at 15-minute intervals used in the analysis.

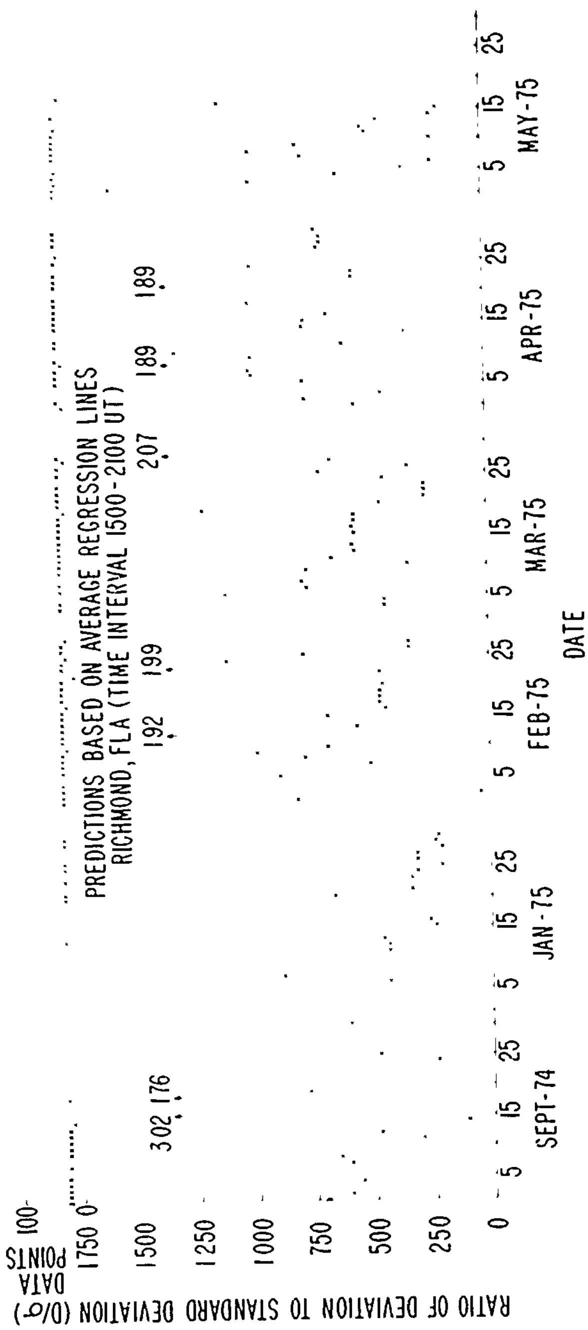

Figure 5: Same as 4, except that the ratios are computed only for the time period 1500-2100 UT.

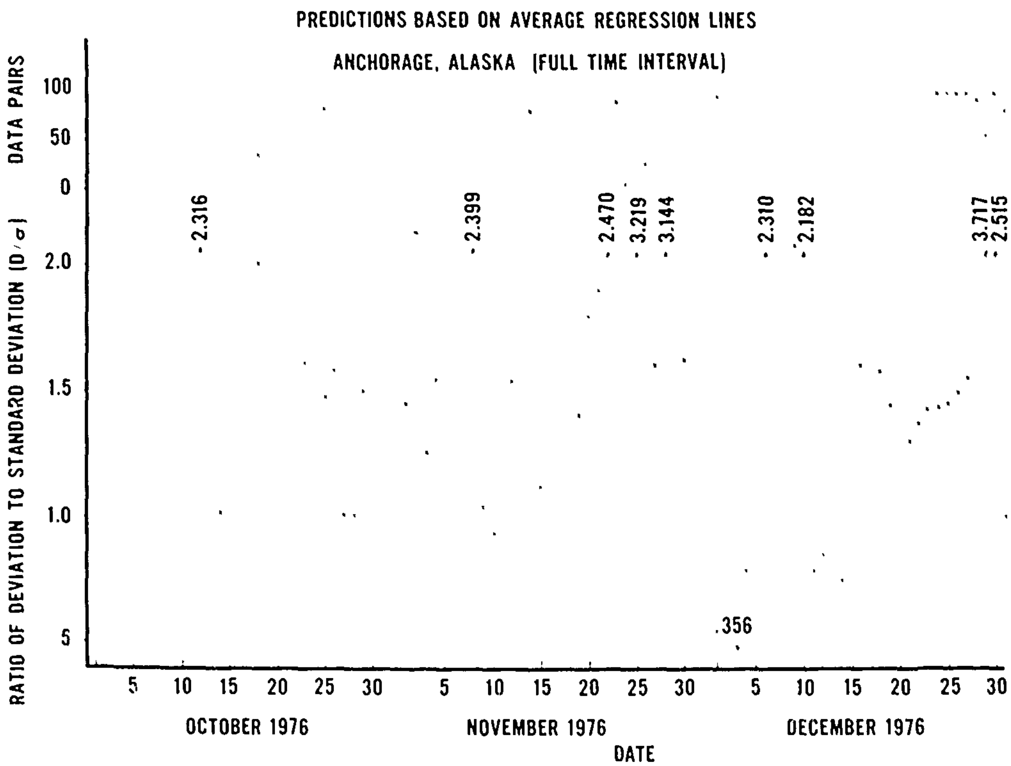

Figure 6: The variation of the ratio $|D| / \sigma$ for Anchorage, AK, for the time period October 1976-December 1976, calculated for full diurnal periods by average regression lines obtained by Richmond, FL-Anchorage, AK data sets. ($|D| \equiv$ diurnal average of the deviations of the computed TEC values from observed ones; $\sigma \equiv$ monthly standard deviations of the Anchorage data). The arrows and the corresponding numerical values are for those values of the ratio which exceed the scale of the Figure. Also indicated in the upper portion of the Figure are the number of TEC data pairs at 15-minute intervals used in the analysis.

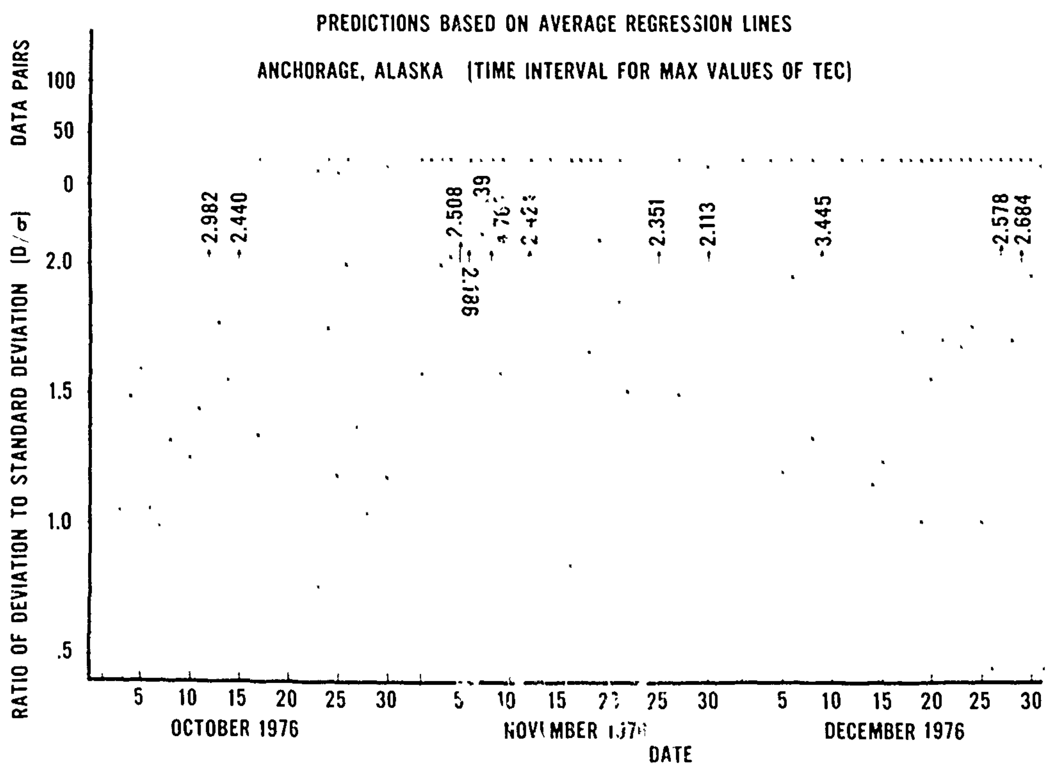

Figure 7: Same as Figure 6, xcept that the ratios are computed only for the time period 1500-2300 UT (Richmond), and the correspondingly shifted Anchorage time period.

change substantially (as compared to the above case).

As Fig. 6 indicates, the daily average of the ratios $|D| / \sigma$ for Anchorage is for the most part, smaller than two, (i.e., on the average, the deviation of the computed Anchorage TEC values from the corresponding Richmond TEC values is, in general, within two standard deviations of the Anchorage data). As in the Fort Monmouth-Richmond data sets the diurnal behavior of the ratio is such that the ratio is higher during the night than during the day. In addition the figure indicates that the ratio is larger, on the average, in October than in the following two months. This occurs despite the fact that the coefficient was, on the average, higher in October, declined in November and declined further in December (due to changes in TEC diurnal shapes associated with changing separation in sunrise and sunset times at the two locales). As with the Fort Monmouth-Richmond case, the ratio here does not change substantially (as compared to the above case) when the average regression lines are forced to pass through the actual data points at the two locations at 0200 UT Richmond time (and the correspondingly shifted Anchorage time). The disadvantage of using this technique for possible operational application is, of course, the inavailability of any data points at the locale where the predictions are to be made.

Since the total signal time-delays are largest during the day and thus, introduce significant errors in navigation and radar systems, it is appropriate to examine the ratio $|D| / \sigma$ during the time when TEC is diurnally larger, i.e., between 1500 and 2100 UT (Richmond, Fort Monmouth times and corresponding Anchorage time).

For the Fort Monmouth-Richmond case Figure 5 indicates that the ratio $|D| / \sigma$, obtained by average regression line for the day period, are substantially lower than the corresponding ratios for the full diurnal periods (Figure 4). This happens despite the fact that D is smaller during the night (although σ is also small compared to its day values). The fact that the bulk of the data indicates that the ratio falls below 1 is encouraging since both correlation methods yield "predicted" TEC values that fall within the monthly standard deviation of the data during the time period when the presence of TEC poses the source of largest error.

For the Richmond-Anchorage case a similar statement cannot be made. On the average, the ratio is not markedly different for the full time interval and for the time interval for maximum value of TEC.

CONCLUSIONS

The high correlation of signal time delay variation at two sets of locale separations, one widely separated by latitude, and the other widely separated by latitude and longitude (and hence by local time), prompted the examination as to whether time-delay data at one locale may be "predicted" if continuous corresponding data were available at the other locale. The correlation is high, in part, due to the 24 hour periodicity of the data. It is precisely this periodicity, however, that gives the "prediction" technique employed here its accuracy. The variation of the time delay is the highly correlatable quantity, and thus, the whole data set - if available - should be used in the prediction scheme.

Monthly average regression lines were used in the analysis. The slopes of the average monthly regression lines were within $\pm$ 20% from their average for the whole period. The intercepts of the monthly lines of regression were considerably more scattered.

For the two locales separated mainly in latitude (Fort Monmouth-Richmond) the deviation of the "predicted" data from the observed data was for the most part, within one standard deviation of the monthly data set. For daytime period, when the error introduced by the time-delay is greatest, the ratio $|D| / \sigma$ was even lower. When an average regression line for the entire period considered was calculated (i.e., the average of six monthly averages), the bulk of the "predicted" data was still within one standard deviation of the monthly data set. The ratio is often high during time periods characterized by ionospheric disturbances.

For the two locales widely separated by latitude and longitude (Richmond-Anchorage), the deviation of the "predicted" data from the observed data was, for the most part, within two standard deviations of the monthly data set. When an average regression line for the entire period was used, the bulk of the "predicted" data was still within the two standard deviations of the monthly data sets.

Since the monthly value of the standard deviation is $\sim$25% of the absolute value of the time delay, the method of prediction outlined here appears to have the capability of correcting the time delay due to the ionosphere to within $\sim$25% for stations separated in latitude, and $\sim$50% for stations widely separated in latitude and longitude.

REFERENCES

(1) H. Soicher, "Ionospheric and Plasmaspheric Effects in Satellite Navigation Systems", IEEE Trans. Antennas & Propagation, Vol. Ap-25, No. 5, Sep 77.

(2) K. Davies, R. B. Fritz, and T. B. Gray, "Measurement of Columnar Electron Contents of the Ionosphere and Plasmasphere", J. Geophysical Research, Vol. 81, p.16, June 1, 1976.

(3) H. Soicher, "The ATS-6 Radio Beacon Experiment", Nature, Vol. 253, pp.252-254, January 24, 1975.

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